

# LATE EMISSION FROM THE TYPE Ib/c SN 2001em: OVERTAKING THE HYDROGEN ENVELOPE

Nikolai N. Chugai

*Institute of Astronomy, RAS, Pyatnitskaya 48, 109017 Moscow, Russia*

and

Roger A. Chevalier

*Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA  
22903, USA*

rac5x@virginia.edu

## ABSTRACT

The Type Ib/c supernova SN 2001em was observed to have strong radio, X-ray, and  $H\alpha$  emission at an age of  $\sim 2.5$  yr. Although the radio and X-ray emission have been attributed to an off-axis gamma-ray burst, we model the emission as the interaction of normal SN Ib/c ejecta with a dense, massive ( $\sim 3 M_{\odot}$ ) circumstellar shell at a distance  $\sim 7 \times 10^{16}$  cm. We investigate two models, in which the circumstellar shell has or has not been overtaken by the forward shock at the time of the X-ray observation. The circumstellar shell was presumably formed by vigorous mass loss with a rate  $\sim (2 - 10) \times 10^{-3} M_{\odot} \text{ yr}^{-1}$  at  $\sim (1 - 2) \times 10^3$  yr prior to the supernova explosion. The hydrogen envelope was completely lost, and subsequently was swept up and accelerated by the fast wind of the presupernova star up to a velocity of  $30 - 50 \text{ km s}^{-1}$ . Although interaction with the shell can explain most of the late emission properties of SN 2001em, we need to invoke clumping of the gas to explain the low absorption at X-ray and radio wavelengths.

*Subject headings:* stars: mass-loss — supernovae: general — supernovae: individual (SN 2001em)

## 1. INTRODUCTION

The supernova SN 2001em was discovered on 2001 September 20 (Papenkova & Li 2001) in the galaxy UGC 11794 ( $z = 0.01935$ ). With an apparent magnitude of about 18.6 and

absolute magnitude of  $M \approx -16$  at the time of discovery (for  $D = 83$  Mpc), the supernova was present in an unfiltered image on September 15 but not on September 5 at a level of 19.5 mag (Papenkova & Li 2001). The spectrum on 2001 October 20 was of Type Ib or Ic a month after maximum brightness (Filippenko & Chornok 2001). There is little doubt that SN 2001em was discovered early, probably before maximum light. We adopt 2001 September 10, i.e. JD=2452163, as the time of explosion. The 5 day uncertainty in the age is of no consequence for the interpretation of the late observations considered here.

Two years after the explosion, on 2003 October 17, SN 2001em was detected at radio wavelengths with the VLA at 3.6 cm. Between then and 2004 January 30, the flux at 3.6 cm increased by a factor of  $\sim 1.3$  (Stockdale et al. 2004), and by a factor of 1.56 to 2004 July 1 (Stockdale et al. 2005). The spectrum in the range 2 – 6.2 cm was nonthermal,  $F_\nu \propto \nu^{-0.37}$  (Stockdale et al. 2004). The high radio luminosity  $\sim 2 \times 10^{28}$  erg s $^{-1}$  Hz $^{-1}$  at 6 cm (Stockdale et al. 2004) is unprecedented for a SN Ib/c at this age. Moreover, X-ray observations on 2004 April 4 (day 937) with *Chandra* revealed X-ray emission in the 0.5 – 8 keV band with a luminosity of  $\sim 10^{41}$  erg s $^{-1}$  (Pooley & Lewin 2004), again unprecedented for a SN Ib/c at this age.

The circumstellar (CS) medium in the immediate vicinity of SNe Ib/c is presumably shaped by a Wolf-Rayet (WR) type wind. The interaction with this wind is normally expected to produce early radio emission that decays with a fairly steep power law in time (e.g., SN 1983N, Weiler et al. 1986). Although the emission would normally be undetectable at an age of 2 years, Stockdale et al. (2004) undertook late observations of SNe Ib/c based on the suggestion that strong late radio emission could be caused by the interaction of a misaligned relativistic jet with the WR wind (e.g., Paczyński 2001). Granot & Ramirez-Ruiz (2004) discussed misaligned jet and CS interaction models for the late emission from SN 2001em and concluded that the misaligned jet model was favored. A prediction of their model was that the radio source should be resolvable with VLBI (very long baseline interferometry) observations, with an angular size  $\gtrsim 2$  mas. VLBI observations have been undertaken by 2 groups (Stockdale et al. 2005; Bietenholz & Bartel 2005), both of which failed to resolve the source at the predicted size; Bietenholz & Bartel set an upper limit on the major axis angular size of 0.59 mas. Although the VLBI observations do not support the misaligned jet model, the model might not be ruled out if there is relativistic motion of a compact radio source.

However, detection of a strong H $\alpha$  emission line with FWHM of 1800 km s $^{-1}$  on 2004 May 7 (Soderberg, Gal-Yam, & Kulkarni 2004) is not readily explained in the misaligned jet model. This type of emission is observed from supernovae which are undergoing strong CS interaction and usually associated with Type II in supernovae (e.g., Filippenko 1997). The

high radio and X-ray luminosities of SN 2001em at an age  $\sim 10^3$  days are comparable to those of bright Type IIn supernovae (e.g., SN 1986J, SN 1988Z) at a similar age. Given this similarity, we propose a model of SN 2001em that accounts for the observed phenomena by interaction of a SN Ib/c with a dense CS shell that is some distance from the progenitor and was initially part of the H envelope of the progenitor star.

General aspects of our model are discussed in § 2 and more details are in § 3. The model results are compared to observations of SN 2001em in § 4 and the formation of the circumstellar shell is treated in § 5. The conclusions, with attention to the evolutionary status of the SN 2001em progenitor, are in § 6.

## 2. GENERAL CONSIDERATIONS

We assume that SN 2001em exploded as an ordinary SN Ib/c, and the late X-ray, radio and  $H\alpha$  emission were the outcome of the ejecta interaction with a dense CS hydrogen shell lost by the progenitor star. This conjecture implies that the CS environment around SN 2001em was shaped by two episodes of mass loss: heavy mass loss in a slow red supergiant wind (possibly in a common envelope phase or a superwind phase) and a subsequent rarefied, fast WR wind. This WR wind caused the formation of a dense CS shell by the interaction of the fast wind with a slow dense wind (e.g., Kahn 1983).

The WR stage following the loss of the hydrogen envelope was relatively brief, so the stellar mass could not have decreased significantly at this stage. We expect, therefore, that the SN 2001em presupernova was the He core of a massive star. A related example is SN 1993J, which originated from a “typical” mass range  $13 - 16 M_\odot$  and got rid of almost all the H envelope (Woosley et al. 1994). For SN 2001em, we adopt an ejecta mass of  $M \approx 2.5 M_\odot$  and an energy of  $E \approx 1.6 \times 10^{51}$  erg, similar to parameters found for SN 1993J (e.g., Utrobin 1994); in § 4.1, we consider variation of these parameters. With the adopted parameters, the typical velocity of SN material is  $v_{\text{sn}} = (2E/M)^{1/2} \approx 8 \times 10^8 \text{ cm s}^{-1}$ . Assuming that X-rays from SN 2001em at  $t \approx 937$  d detected by *Chandra* (Pooley & Lewin 2004) correspond to the stage of strong interaction with the CS shell, the radius of the CS shell is then  $R_{\text{cs}} \sim v_{\text{sn}} t \sim 6 \times 10^{16} \text{ cm}$ . The typical supernova velocity (or less) must be chosen if the supernova energy has substantially thermalized; on the other hand, the rising radio flux implies that the interaction is not highly evolved. The hydrogen envelope was presumably lost during the red supergiant stage with a velocity  $\sim 10^6 \text{ cm s}^{-1}$ . The CS shell was likely accelerated by the WR wind to a velocity  $u_{\text{cs}} \sim 20 \text{ km s}^{-1}$ , so the age may be  $R_{\text{cs}}/u_{\text{cs}} \sim 10^3 \text{ yr}$  (§5).

The shock interaction of freely expanding SN ejecta ( $v = r/t$ ) with a CS shell proceeds through the formation of a double shock interface layer with the forward shock accelerating the CS gas and the reverse shock decelerating SN ejecta. The swept up hot gas between the two shocks is responsible for X-rays, while the accelerated electrons and amplified magnetic field in the interaction zone bring about the synchrotron radio emission (Chevalier 1982; Chevalier & Liang 1989). The  $H\alpha$  emission line with a full width at half maximum (FWHM) of  $\sim 1800 \text{ km s}^{-1}$  detected on day 970 (Soderberg, Gal-Yam, & Kulkarni 2004) is probably emitted by the CS gas accelerated in the forward shock, since the SN ejecta are devoid of hydrogen. The  $H\alpha$  profile has no apparent extended wings beyond a velocity of  $2000 \text{ km s}^{-1}$  (Soderberg, Gal-Yam, & Kulkarni 2004), which implies that the bulk of the line-emitting gas in the forward shock moves with velocities  $\leq 2000 \text{ km s}^{-1}$ .

Two possibilities for the origin of the high velocity hydrogen in the forward shock are: (i) a shock wave with a velocity  $\sim 2 \times 10^3 \text{ km s}^{-1}$  that passed through the smooth dense CS shell was radiative, so a cool dense shell formed between the shock wave and the contact surface; (ii) the dense CS shell was clumpy, so the clouds were first shocked by slow radiative shocks, and then fragments of the shocked clouds were accelerated in the forward shock up to  $\sim 2 \times 10^3 \text{ km s}^{-1}$ , similar to the scenario proposed for the  $H\alpha$  emission in SN 2002ic (Chugai, Chevalier, & Lundqvist 2004).

The temperature of the forward shock with a velocity of  $\sim 2 \times 10^3 \text{ km s}^{-1}$  is about 5 keV, far below the 80 keV estimated from *Chandra* observations on day 940 (Pooley & Lewin 2004). The reverse shock can be much hotter. As a result of the sudden collision of the rarefied outer SN layers with the dense CS shell, the swept up shell at the SN/CS interface is strongly decelerated because of a high CS/SN density contrast  $\rho_{\text{cs}}/\rho_{\text{sn}}$ . The swept up shell velocity

$$v_s \approx v_{\text{sn}}(\rho_{\text{sn}}/\rho_{\text{cs}})^{1/2}, \quad (1)$$

where  $v_{\text{sn}}$  is the velocity of SN ejecta at the reverse shock, is low and, consequently, the reverse shock velocity  $v_{\text{sn}} - v_s$  is high enough to provide a high temperature of the shocked SN ejecta. An additional factor that favors a high temperature at the reverse shock is an average molecular weight of ejecta that is larger than for normal cosmic abundances. For the ionized He composition of SN Ib/c,  $\bar{\mu} = \rho/nm_p = 1.33$ , so the velocity of the reverse shock must be only  $\approx 5500 \text{ km s}^{-1}$  to yield a shock temperature of 80 keV. With the velocity of the swept up shell  $\approx 2000 \text{ km s}^{-1}$ , the boundary ejecta velocity should be  $\approx 8000 \text{ km s}^{-1}$  at the time of X-ray observation. The actual picture may be more complicated, because the X-ray emission is a combination of the radiation from both shocks with different temperatures.

We now estimate the mass of the shocked SN ejecta assuming that the reverse shock is the dominant component. With the standard bremsstrahlung cooling function  $\Lambda = 1.6 \times$

$10^{-27}T^{1/2}Z^2$ , where  $Z = 2$  is the ion charge for pure He, we find that the observed X-rays with  $T = 9 \times 10^8$  K (i.e. 80 keV) and luminosity  $L_x \approx 10^{41}$  erg s $^{-1}$  require an emission measure  $EM \approx 5 \times 10^{62}$  cm $^{-3}$ . To estimate the mass of the shocked ejecta, the volume of the reverse postshock layer between the reverse shock and the contact surface should be determined. Let SN ejecta with a power law density distribution  $\rho = \rho_0(v/v_0)^{-k}$  for  $v > v_0$  and  $\rho = \rho_0$  at  $v < v_0$  collide with a dense narrow CS shell. The ratio of the radius of the reverse shock to the radius of the contact surface  $\xi = r_{rs}/R_c$  in that case is (Chevalier & Liang 1989)

$$\xi = \left( \frac{4k - 20}{4k - 15} \right)^{1/3}. \quad (2)$$

Substituting  $k = 9$  gives  $\xi \approx 0.91$ . For  $R_c \sim 6 \times 10^{16}$  cm,  $\xi = 0.91$ , and  $EM \approx 5 \times 10^{62}$  cm $^{-3}$ , the mass of the shocked ejecta is  $\sim 0.8 M_\odot$ . Momentum conservation implies that the CS shell mass required to decelerate  $M_1 \sim 1 M_\odot$  of the SN ejecta with the typical velocity of  $v_{sn} \sim 8000$  km s $^{-1}$  down to  $v_s \sim 2000$  km s $^{-1}$  is  $M_2 \approx M_1(v_{sn}/v_s - 1) \approx 3 M_\odot$ . Given the age of the CS shell of  $\sim 10^3$  yr, the last episode of the hydrogen envelope removal thus occurred with a mass loss rate of  $\sim 3 \times 10^{-3} M_\odot$  yr $^{-1}$ . Below we present a more detailed interaction model that will confirm this general picture, although with some modifications regarding the interpretation of the X-ray spectrum (§4.1).

This consideration of the X-ray luminosity shows that the mass of the CS shell must be comparable to the ejecta mass, so that the supernova energy is substantially thermalized. Although the radio luminosity was rising at an age of 770–1000 days, we expect that the luminosity cannot rise much further because the interaction energy cannot keep increasing. This is consistent with the fact that the luminosity of SN 2001em is comparable to that of the most luminous radio and X-ray supernovae at a comparable age. The situation can be compared to that in SN 1987A, which is known to have a dense ring at a radius of  $6 \times 10^{17}$  cm, about an order of magnitude larger than the dense shell inferred here. The radio flux from SN 1987A started to rise at an age of 3 yr (Manchester et al. 2002), but at a luminosity level orders of magnitude smaller than the luminosity observed in SN 2001em; the initial interaction is with the outer, high velocity, low density ejecta, which have only a small part of the supernova energy. In addition, the mass in the CS shell is probably considerably less than the ejecta mass, so that only a fraction of the supernova energy will have been thermalized at the time that the CS shell is swept up.

### 3. THE MODEL

#### 3.1. Hydrodynamic Interaction

We consider freely expanding ( $v = r/t$ ) SN ejecta interacting with a CS environment consisting of a massive dense CS shell placed between the WR wind (inner zone) and the slow red supergiant wind (outer zone). The SN ejecta mass is taken to be  $M \approx 2.5 M_\odot$ , the kinetic energy is  $E \approx 1.6 \times 10^{51}$  erg, and the density distribution has a flat inner zone,  $\rho = \rho_0$  at  $v < v_0$ , and a power law outer layer,  $\rho = \rho_0(v/v_0)^{-k}$  for  $v > v_0$  with  $k = 9$ .

The WR wind is set by the wind density parameter  $w_1 = \dot{M}_1/u_1 = 6.3 \times 10^{12}$  g cm $^{-1}$  which corresponds to the choice  $\dot{M}_1 = 10^{-5} M_\odot$  yr $^{-1}$  and the wind velocity of  $u_1 = 1000$  km s $^{-1}$ . This wind has little effect on the late time interaction because of its low density, and we neglect the fact that the WR wind has to pass through a shock wave inside the CS shell. The assumed width of the dense CS shell is  $R_2 - R_1 = \Delta R \approx 0.1R$ , where  $R$  is the average radius of the CS shell. The density in the CS shell is characterized by the density parameter  $w_2$ , which is defined by the shell radius and the shell mass with the assumed  $\Delta R/R$  ratio. In § 5.2, we show that the assumed shell thickness and density are consistent with expectations. The outer wind at  $r > R_2$  is presumably the slow dense wind of a red supergiant and we take  $w_3 = 10^{15}$  g cm $^{-1}$ , an intermediate value between the wind densities expected for a SN IIP and a bright SN IIL. We explored other values and found that, provided  $w_3 \lesssim 10^{16}$  g cm $^{-1}$ , the results are not sensitive to this parameter. The two versions of the density distribution of the CS matter (CSM) that will be used below are shown in Fig. 1. The models differ in the radius of the CS shell. In model A, the interaction with the CS shell is not yet finished by the time of the X-ray observation ( $t = 937$  d), while model B, with a smaller shell radius, represents a situation where the CS shell was swept up prior to the X-ray observation.

The hydrodynamic evolution of the SN interaction is treated in the thin shell approximation (Chevalier 1982), i.e. the layer between forward and reverse shocks is replaced by a thin layer. This description yields the radius of the thin shell  $R_s$ , the shell velocity  $v_s$ , and the boundary velocity of the unshocked SN ejecta  $v_{\text{sn}}$  at an age  $t$ . The velocities of the forward shock ( $\approx v_s$ ) and reverse shock ( $v_{\text{sn}} - v_s$ ) provide us with kinetic luminosities for both shocks. The kinetic luminosities can be converted into X-ray luminosities if they are multiplied by a factor  $t_e/(t_e + t_c)$  which is determined by the ratio of the cooling time  $t_c$  and the time of accumulation of the shock internal energy  $t_e = (d\ln E/dt)^{-1}$ . Usually,  $t_e = t$  is assumed (e.g., Chevalier & Fransson 1994; Chugai 1992) and this is appropriate for interaction with a smooth wind. In the case of a collision with a narrow CS shell one expects  $t_e < t$ , so it is more appropriate to use the directly calculated value of  $t_e$ . However, this approach based upon the instant kinetic luminosity is not valid at a very late epoch, when

the forward shock has overrun the dense shell ( $R_s > R_2$ ) and propagates into the rarefied wind. The radiation from the large mass of shocked CS gas left behind by the previous interaction should dominate. We treat the thermal history of the outer hot gas by solving the time-dependent energy balance with the internal energy generation in the forward shock, adiabatic cooling (dominant term), and radiative cooling. To obtain the density of the outer hot gas, we assume that the shell expands homologously and  $\Delta R/R = 0.1$ . This approximation is supported by the fact that the spherical expansion of a gas cloud proceeds in a self-similar way with a boundary velocity comparable to the initial thermal velocity (Zel’dovich & Raizer 1967), i.e. the shell speed in our case.

The model simulations show that model A assuming a smooth CS density predicts a larger absorption of X-rays than indicated by the observations. Therefore, we assumed a clumpy structure of the CS shell to reduce the absorption. In model B the X-rays do not constrain the structure of the CS shell, because it has been already shocked at the time of observation. We approximate the interaction with a clumpy CS shell by including the clumpiness *only* for the absorption computation, while the interaction dynamics and the unabsorbed X-ray luminosity of both shocks are described assuming a *smooth* CS shell with an average density. This approximation, although crude at first glance, is justified if CS clouds entering the forward shock fully deposit their kinetic energy, which means that clouds are completely crushed, fragmented and mixed within the forward shock. This picture amounts to the assumption that, for CS clouds of radius  $a$ , the cloud crushing time  $t_{cc} = a/v_c$  (Klein, McKee, & Colella 1994) is significantly less than the time required for a CS cloud to cross the forward shock region with width  $h$ , i.e.,  $t_{cc} \ll (h/R)R/v_s$ . We return to this issue below (§4.1).

The question arises of whether model A with a smooth density can adequately represent the X-ray spectrum. The spectrum of the forward shock in the cloudy CS gas is a combination of radiation from the hot intercloud gas and cooler cloud shocks, which cannot be treated properly in the smooth approximation. Fortunately, the X-ray emission of cloud shocks does not affect markedly the amount of internal energy generated by the forward shock in the intercloud gas. The point is that the total kinetic luminosity of slow cloud shocks is a factor of  $\chi_1^{-1/2} \ll 1$  (where  $\chi_1 \gg 1$  is cloud-to-intercloud density ratio in the forward shock) smaller than the kinetic luminosity of fast bow shocks. Therefore, most of the internal energy in the forward shock region resides in the hot intercloud gas. The approximation of a smooth forward shock region for the clumpy model A may be satisfactory for the X-ray spectrum in the range  $E > 1$  keV. Yet a sizable amount of the kinetic luminosity of the forward shock interacting with a clumpy CS shell is expected to be emitted by cloud shocks in the soft band ( $E < 0.5$  keV). Most of this radiation is presumably absorbed and re-emitted in the optical/UV band outside of the X-ray band of interest.

### 3.2. X-ray and Radio Absorption Model

The observed X-ray spectrum is affected by four cool components, including (1) galactic absorption and intrinsic absorption in (2) unshocked SN ejecta; (3) unshocked CS gas; and (4) shocked cool H $\alpha$ -emitting gas. The reddening towards SN 2001em is  $E(B - V) = 0.1$  (Schlegel, Finkbeiner, & Davis 1998), which corresponds to a column density  $N_{\text{H}} = 6 \times 10^{20} \text{ cm}^{-2}$  (Spitzer 1978). We take this value as the total column density in the first cool component, neglecting interstellar absorption in the host galaxy. The SN ejecta can absorb X-rays, despite the fact that ejecta gas can be heated up to  $\sim 6 \times 10^4 \text{ K}$ . The smooth outer wind in the region  $r > R_2$  irradiated by X-rays becomes hot ( $T > 10^6 \text{ K}$ ) for  $w_3 \leq 10^{16} \text{ g cm}^{-1}$  and is not a significant absorber of radio. However the outer wind absorbs X-rays, although carbon and oxygen may be ionized up to He- and H-like ions.

As noted above, the CS shell in model A has to be clumpy to be consistent with the low X-ray absorption. The optical depth of the clumpy CS shell is computed as

$$\tau(E) = \int_{R_s}^{R_b} \pi a^2 N_V (1 - e^{-\tau_c}) dr, \quad (3)$$

where  $R_b$  is the outer radius of the CS region taken to be  $1.5 \times 10^{17} \text{ cm}$ ,  $N_V = f/(4\pi a^3/3)$  is the number density of clouds,  $f = (1 - \xi)/\chi$  is the cloud filling factor,  $\xi$  is the mass fraction of the intercloud phase (we take  $\xi = 0.1$ ) and  $\chi$  is the ratio of cloud density to the local average density,  $\tau_c = (4/3)ak(E)\rho_c$  is the cloud average optical depth, and  $k(E)$  is the absorption coefficient for X-rays with energy  $E$ . The occultation optical depth of the CS shell along the radius,  $\tau_{\text{oc}} = \pi a^2 N_V \Delta R$ , should be of order unity or less to provide reasonable transparency. With fixed  $\xi$  and  $\chi$ , the only remaining parameter that determines  $\tau_{\text{oc}}$  is the cloud radius  $a$ . The X-ray absorption by the unshocked SN ejecta is determined by integrating the radiation transfer equation along rays with different impact parameters for the assumed density distribution. We found that the absorption of radio emission by SN material has a small effect on the emergent spectrum, so we treat it approximately in terms of the average values of the electron number density and the temperature of the ejecta irradiated by X-rays.

In model B, only the outer wind and fourth component (H $\alpha$ -emitting gas) can provide intrinsic X-ray absorption. To treat the latter we assume that 10 – 30% of the shocked CS gas resides in the cool H $\alpha$ -emitting gas; the result is insensitive to the value in this range. This gas is probably distributed in the form of heterogeneous structures (knots, filaments, sheets) imbedded in the hot gas of the forward shock. We assume that hot and cool gas are homogeneously mixed. In this case the absorption by the fourth component is characterized by the optical depth  $\tau_{4,\text{av}}$  for the average column density, and by the occultation optical



depth (the average number of clouds along the radius)  $\tau_{4,\text{oc}}$ . The optical depth for the X-ray radiation transmitted through the forward shock layer derived from Eq. (3) is then

$$\tau_4 = \tau_{4,\text{oc}}[1 - \exp(-\tau_{4,\text{av}}/\tau_{4,\text{oc}})]. \quad (4)$$

For photons emitted in a layer along the normal to the surface, the intensity of escaping radiation is  $I = I_0[1 - \exp(-\tau_4)]/\tau_4$ , where the  $I_0$  is the unabsorbed intensity. We adopt the same expression for the flux of radiation escaping from layer  $F = F_0[1 - \exp(-\tau_4)]/\tau_4$ . However, for the radiation escaping through the inner surface we additionally have to take into account the absorption in the SN ejecta ( $e^{-\tau_3}$ ) and absorption in the  $\text{H}\alpha$ -emitting gas at the opposite side of the forward shock ( $e^{-\tau_4}$ ). For the radio emission, we assume also that the  $\text{H}\alpha$ -emitting material is homogeneously mixed with the radio-emitting shell. This is an approximation to a complicated situation in which the forward and reverse shock regions both contribute to the acceleration of relativistic electrons and magnetic field amplification, so, generally, the radio-emitting shell and the  $\text{H}\alpha$ -emitting material may not overlap exactly.

The free-free absorption of the radio emission by the CS shell depends on the ionization fraction of hydrogen ( $x$ ) and the electron temperature of the cool components. These values are calculated taking into account that the absorbed energy of X-rays is shared between Coulomb heating, excitation and ionization. We assume that the latter two processes have equal branching ratios. For the Coulomb heating we adopt a branching ratio  $x^{0.24}$ , a reasonable approximation if the ionization fraction  $x > 10^{-3}$  (Kozma & Fransson 1992). The cooling term in the energy balance is calculated using a standard cooling function for solar composition (Sutherland & Dopita 1993). If the thermal balance cannot maintain the cool phase ( $T \leq 10^5$  K) we adopt full ionization and consider this gas as transparent. The typical value of the ionization fraction of the clouds at about 900 day is  $x \approx 0.3$  and temperature  $T_e \approx 13000 - 14000$  K, while the intercloud gas is hot ( $T_e > 10^6$  K) and thus does not absorb radio emission. For the  $\text{H}\alpha$ -emitting gas the typical ionization is  $x \sim 0.01$  and temperature  $T_e \approx 10^4$  K. In the SN ejecta the helium is fully ionized and the electron temperature is  $T_e \approx 6 \times 10^4$  K.

The unabsorbed X-ray spectrum is modelled by thermal bremsstrahlung with a non-relativistic Gaunt factor (Itoh et al. 2000). The photoionization cross sections for the absorption by electrons of K and L shells with  $2s$  and  $2l$  subshells are taken from Verner et al. (1993). Solar abundances are assumed for the CSM, while the SN Ib/c ejecta are approximated by a mixture of 65% He, 33% O, and 2% Fe by mass.

## 4. RESULTS

### 4.1. CS Interaction Models and X-ray Emission

We now discuss models that fit the basic observations of SN 2001em. The parameters of the CS shell for models A and B, namely, the inner and outer radius of the CS shell ( $R_1$  and  $R_2$ ), the density parameter of the CS shell ( $w_2$ ), and the total mass of the CS shell are given in Table 1 (see also Fig. 1). The total mass of the CS shell is  $\approx 2.3 - 3 M_\odot$  (Table 1), similar to the preliminary estimate in § 2. The evolution of the major output parameters is presented in Fig. 2. The plot shows the radius of the thin shell (contact surface), the velocity of the thin shell and of the boundary of the SN ejecta, the unabsorbed X-ray luminosity, and the temperature of forward and reverse shocks. Here we assume a smooth CS shell so both shocks are adiabatic; however, the forward shock between days 400 and 500 is very close to the radiative regime with  $t_c/t_e \sim 1.5 - 2$ .

After about day 200 a shell formed during the interaction of the SN with the WR wind collides with the inner boundary of the dense CS shell. There is subsequent rapid deceleration from  $\sim 25000 \text{ km s}^{-1}$  down to  $1200 - 1300 \text{ km s}^{-1}$ , followed by a period of steady acceleration (e.g., Chevalier & Liang 1989; Dwarkadas 2005). The collision results in a rise of the X-ray luminosities of both shocks toward their maximum values,  $\sim 10^{41} \text{ erg s}^{-1}$ . The maxima occur at the phase when the CS shell has been swept up, i.e. at  $\approx 1000 \text{ d}$  and  $\approx 900 \text{ d}$  for models A and B respectively. The luminosity of the shocked CS gas remains high after the CS shell has been overtaken; the temperature, however, rapidly decreases for  $t > 1000 \text{ d}$  due to adiabatic cooling. The contribution of the forward shock to the internal energy of the shocked CS gas at a late epoch is negligible for  $t < 2000 \text{ d}$ . At the time of the  $\text{H}\alpha$  observation ( $t = 970 \text{ d}$ ), the thin shell velocity is  $2200 \text{ km s}^{-1}$  in model A and  $3200 \text{ km s}^{-1}$  in model B; both are consistent with the observed  $\text{H}\alpha$  width.

The calculated X-ray spectra for both models (Fig. 3) reproduce the data of Pooley & Lewin (2004) quite satisfactorily. Note that model A has a clumpy CS shell here; a smooth CS shell produces too strong absorption (Fig. 3). The fit quality for both models is comparable to that of the isothermal hot spectrum with  $kT = 80 \text{ keV}$  (Fig. 3, inset) and with external absorption corresponding to  $N_{\text{H}} = 1.6 \times 10^{21} \text{ cm}^{-2}$ , the value reported by Pooley & Lewin (2004). The unabsorbed spectrum in our models is a mixture of the hot ( $kT \sim 100 \text{ keV}$ ) radiation of the reverse shock and “cool” ( $kT \sim 5 - 6 \text{ keV}$ ) radiation of the forward shock with comparable luminosities (Fig. 2). In fact, the cooler component dominates in the range  $\leq 5 \text{ keV}$ . We thus come to a picture in which the data are reproduced by a relatively cool spectrum subjected to the intrinsic absorption by the clumpy cool material, so the emergent spectrum successfully mimics the observed hot isothermal spectrum ( $\sim 80$

keV) with a smooth external absorber. Although the general picture presented earlier (§ 2) is based on the view that the X-rays are represented by a hot isothermal spectrum, the mass estimate is not appreciably changed, because the luminosity of the hot component is comparable to the total luminosity.

The H $\alpha$ -emitting gas is characterized by an occultation optical depth  $\tau_{\text{oc},4} = 0.5$  in model A and  $\tau_{\text{oc},4} = 1.5$  in model B. The cloudy CS shell in model A has  $\tau_{\text{oc},2} = 1$ . We adopt a cloud density contrast (cloud-to-average)  $\chi = 10$ , which leads to a cloud radius  $a = 4.7 \times 10^{14}$  cm. The result is not sensitive to variation of  $\chi$  in the range 3 – 30. With these parameters we can check the condition for the approximation of a smooth density in model A, i.e.  $a \ll hv_c/v_s = a_0$  (§ 3.1). From momentum conservation, the ratio of the cloud shock velocity to the forward shock velocity  $v_c/v_s \approx (4\xi/\chi)^{1/2} \approx 0.2$ . Assuming the forward shock width  $h \approx 0.1R \approx 7 \times 10^{15}$  cm, this gives the upper limit  $a_0 = 1.4 \times 10^{15}$  cm which is three times larger than the cloud radius  $a = 4.7 \times 10^{14}$  cm in model A. The condition for the smooth density approximation is thus barely met.

To consider variations in the supernova parameters, we explored “low energy,”  $M = 2.5 M_\odot$ ,  $E = 10^{51}$  erg, and “high mass,”  $M = 4 M_\odot$ ,  $E = 1.6 \times 10^{51}$  erg, versions of model A. We found that the X-ray spectrum is well reproduced in both cases, if the CS shell radius is smaller by a factor 0.8 – 0.84. The thin shell velocity is 1800 km s $^{-1}$  in the low energy case and 2000 km s $^{-1}$  in the high mass case, i.e. still consistent with the H $\alpha$  line profile. The uncertainty in the SN ejecta parameters thus results in minor variations in the model parameters.

## 4.2. Radio Emission

The collision of the SN ejecta with the CS environment is expected to produce synchrotron radio emission as a result of the relativistic particle acceleration and magnetic field amplification in the shock wave region (Chevalier 1982). As noted above, the situation with the radio evolution of SN 2001em is similar to SN 1987A, in which the radio flux showed steady growth after the forward shock began to interact with the dense H II region in the red supergiant wind (Chevalier & Dwarkadas 1995; Manchester et al. 2002). Here we concentrate on the absorption effects of both free-free absorption and synchrotron self-absorption, and consider some implications of the radio evolution. Our analysis is based on the assumptions that relativistic electrons with a power law spectrum,  $dN/dE = KE^{-p}$  (the spectral index is  $\alpha = (p - 1)/2$  for  $F_\nu \propto \nu^{-\alpha}$ ), and magnetic field  $B$  are distributed homogeneously in a spherical shell with width  $\Delta R = 0.1R_s$  and radius  $R_s$ ; the radius is provided by the interaction dynamics. The radio-emitting shell is assumed to be homogeneously mixed with the

cool clumpy H $\alpha$ -emitting gas. We assume a minimum energy of the relativistic electrons of 1 MeV, energy equipartition between magnetic field and relativistic particles, and equipartition between relativistic electrons and protons. Given the interaction model, the remaining free parameter is the ratio ( $\zeta$ ) of the energy density of magnetic field plus relativistic particles to the kinetic energy density of the forward shock.

The effects of SSA (synchrotron self-absorption) and free-free absorption on the radio spectrum in model A and model B are shown in Fig. 4 along with data on 2004 January 31 (Stockdale et al. 2004). The optimal parameters are  $\alpha = 0.55$ ,  $\zeta = 0.024$  in model A and  $\alpha = 0.5$ ,  $\zeta = 0.017$  in model B. We found that the variation of the SN ejecta parameters in the low energy and high mass models (§ 4.1) results in a 10% variation of the parameter  $\zeta$  with practically the same fit to the spectrum on day 872. The derived values of  $\zeta$  imply a magnetic field  $B \approx 0.2$  G in both models at the time under consideration. For this magnetic field, synchrotron losses become important (i.e.  $t_{\text{syn}} \sim 1$  yr) at frequencies  $\nu > 2 \times 10^{11}$  Hz. In the observed frequency range ( $\nu < 2 \times 10^{10}$  Hz), the spectrum is not affected by synchrotron cooling.

The spectrum without free-free absorption demonstrates that SSA is significant for  $\nu < 4 \times 10^9$  Hz. The importance of SSA could be deduced from equation (13) of Chevalier (1998), which shows that the size of the radio emitting region at which the shell turns optically thin is comparable to the size of the shell found here. An observation of SN 2001em on 11 March 2005 at 1.6 GHz showed a considerably lower flux than would have been expected from the higher frequency flux evolution (Paragi et al. 2005), which can be interpreted as a low frequency turnover or a sudden flux decline. Our results are consistent with a low frequency turnover. The spectral inversion at  $\nu > 2 \times 10^{10}$  Hz is related to the transparency of absorbing clumps at high frequencies.

The mechanisms for particle acceleration and magnetic field amplification, especially in the case with a cloudy structure of the CS shell, are uncertain. The evolution of the radio flux, therefore, cannot be predicted with confidence. Assuming that the energy of relativistic electrons and magnetic field is a constant fraction of the kinetic energy (i.e.,  $\zeta = \text{const}$ ), we find that in model A the radio flux at 3.6 cm on day 767 is  $\sim 3$  times lower compared to the observed flux, while on day 1025 the model flux is  $\sim 2$  larger. This implies that the parameter  $\zeta$  should drop by factor of three between days 767 and 1025. In model B assuming a smooth CS shell, the flux on day 767 is 30 times lower owing to strong absorption in the CS shell. On the other hand, assuming a clumpy CS shell with the same clumpiness parameters as in model A, we are able to reproduce in model B the flux evolution between day 767 and 1024 with  $\zeta \approx \text{const}$ . This analysis indicates that model B with a clumpy CS shell is somewhat preferred from the point of view of the interpretation of X-ray and radio data.

### 4.3. H $\alpha$ -emitting Gas

As remarked above (§ 2), the H $\alpha$  emission line on day 970 (Soderberg, Gal-Yam, & Kulkarni 2004) indicates the presence of cool shocked CS gas behind the forward shock front. We stress that in model B with the overtaken CS shell, the forward shock is adiabatic for a smooth density distribution and the assumed CS width  $\Delta R/R = 0.1$ . The shock becomes radiative if the density is at least factor of three larger, i.e.  $n \geq 2 \times 10^7 \text{ cm}^{-3}$ . This requires either a factor of three narrower CS shell, i.e.  $\Delta R/R \leq 0.03$ , or, alternatively, the CS shell could be clumpy. The latter option is preferred because the radio data, as noted above, also suggest a clumpy structure for the CS shell in model B. To be consistent with the H $\alpha$  observation, the cool gas in the forward shock of model B must survive at least during  $\sim 100$  days after it has been shocked. This is plausible, although the survival of cool gas in the hot environment is a complicated issue, because it is related to the poorly defined mass exchange between cool and hot phases, especially in the presence of magnetic field.

The dense shocked cool hydrogen re-emits the absorbed X-rays, producing H $\alpha$ . The H $\alpha$  luminosity can be written as a fraction of the X-ray luminosity of the forward shock absorbed by the fast cool hydrogen multiplied by the efficiency  $\eta$  of the H $\alpha$  emission. The fraction of absorbed X-ray radiation with the bremsstrahlung spectrum  $F_E \propto E^{-0.4} \exp(-E/kT)$  (Cox 2000) is  $\sim (E_1/kT)^{0.6}$ , where  $E_1$  is the energy at which the optical depth of the cool hydrogen shell with a mass  $M_{\text{cool}}$  is unity. An energy dependence of the absorption coefficient  $k_x(E) \propto E^{-8/3}$  implies  $E_1 \propto M_{\text{cool}}^{3/8}$ . The expected H $\alpha$  luminosity on day 970 with the temperature of X-ray radiation of the forward shock  $kT = 5 \text{ keV}$  (Fig. 2) is then

$$L_{\text{H}\alpha} = 5 \times 10^{40} \eta L_{\text{x},41} \left( \frac{M_{\text{cool}}}{M_{\odot}} \right)^{0.225}, \quad (5)$$

where  $L_{\text{x},41}$  is the X-ray luminosity of the forward shock in units of  $10^{41} \text{ erg s}^{-1}$ . The efficiency of H $\alpha$  emission according to photoionization models for relevant parameters, i.e. the pressure equilibrium density of cool ( $\sim 10^4 \text{ K}$ ) gas of  $\sim 3 \times 10^{11} \text{ cm}^{-3}$ , column density of  $\sim 10^{22} \text{ cm}^{-2}$ , and X-ray flux of  $\sim 10^6 \text{ erg s}^{-1} \text{ cm}^{-2}$  is  $\eta \sim 0.1$  (Collin-Souffrin & Dumont 1989, model 55). The swept up CS mass in the forward shock on day 970 is  $2 M_{\odot}$  in model A. Assuming one-third of it resides in the cool phase ( $0.7 M_{\odot}$ ) the expected luminosity of H $\alpha$  (Eq. [5]) is then  $\sim 4.5 \times 10^{39} \text{ erg s}^{-1}$  at about day 1000 for  $L_{\text{x},41} = 1$ . A comparable amount of a cool gas in model B would produce a similar H $\alpha$  luminosity. These estimates ignore the clumpiness of the H $\alpha$ -emitting gas that might slightly reduce the luminosity. On the other hand, we also ignored the effect of thermal conductivity that might somewhat increase the H $\alpha$  luminosity. Unfortunately, the observed H $\alpha$  flux is not yet available; its value would provide a useful constraint on models.

An implication of the SN/CSM interaction model is the possible existence of a narrow

H $\alpha$  line from the ionized pre-shock CS gas. For model A the luminosity of the narrow H $\alpha$  is  $\sim 10^{38}$  erg s $^{-1}$  on day 1000, i.e.  $\sim 2\%$  of the broad H $\alpha$  line. In model B with the overtaken CS shell, a narrow H $\alpha$  line is not expected. A search for narrow H $\alpha$  emission could provide a test for the presence of dense unshocked CS gas.

## 5. FORMATION OF THE CS SHELL

### 5.1. Age of the CS Shell

The large mass and high density of the CS shell suggest the following formation scenario: loss of the hydrogen envelope  $\sim 10^3$  yr before the supernova, possibly during a common envelope phase or the superwind phase of a single star (Heger et al. 1997), and the subsequent sweeping up of this matter by the fast wind of the hot He star. We thus envisage three major phases of the CS shell formation: (I) mass-loss of the hydrogen envelope ( $0 < t < t_I$ ); (II) sweeping up the shell by the WR wind ( $t_I < t < t_{II}$ ); and (III) acceleration of the swept up shell by the WR wind ( $t_{II} < t < t_{III}$ ). Garcia-Segura et al. (1996) have simulated this sequence of events, although for different stellar parameters. To estimate the age at the moment of the SN explosion ( $t_{III}$ ), we use the average parameters of our models: final CS shell radius  $r_{III} = 6.5 \times 10^{16}$  cm and the mass of the CS shell  $M_{cs} = 2.7 M_{\odot}$ . The velocity of the mass-loss at stage I is assumed equal to the typical red supergiant escape velocity  $u_{\text{rsg}} = 10$  km s $^{-1}$ , while the mass-loss rate at this stage  $\dot{M}_{\text{rsg}}$  is a free parameter to be determined. For the WR wind, the assumed parameters are the same as stated above, i.e.  $u_{\text{WR}} = 1000$  km s $^{-1}$  and  $\dot{M}_{\text{WR}} = 10^{-5} M_{\odot} \text{ yr}^{-1}$ .

The mass-loss rate at the first stage can be constrained using the following arguments. The minimum value of  $\dot{M}_{\text{rsg}}$  is determined by the condition that at least the two first dynamical phases should pass with the correct final radius of the CS shell ( $r \approx 6.5 \times 10^{16}$  cm). The second phase is needed to build the density of the CS shell up to a value consistent with our models. An upper limit of  $\dot{M}_{\text{rsg}} \approx 0.01 M_{\odot} \text{ yr}^{-1}$  is obtained assuming that the average density parameter  $w_2 \approx 6.5 \times 10^{17}$  g cm $^{-3}$  in our models (Table 1) corresponds to the unperturbed CS shell ejected by the presupernova.

The duration of the first phase is  $t_I = M_{cs}/\dot{M}_{\text{rsg}}$ . To estimate the time length of phase II, we consider the interaction of two steady winds. The interaction proceeds in the pressure-dominated regime, i.e. the WR wind termination shock has a relatively small radius. In that case the swept-up shell expands with the constant velocity  $\lambda u_{\text{rsg}}$  determined by the cubic

equation (Kahn 1983)

$$\lambda(1 - \lambda)^2 = \frac{1}{3} \frac{\dot{M}_{\text{WR}}}{\dot{M}_{\text{rsg}}} \left( \frac{u_{\text{WR}}}{u_{\text{rsg}}} \right)^2. \quad (6)$$

In phase III, a thin shell of mass  $M$  is driven by the pressure of the shocked WR wind with the kinetic luminosity  $L_{\text{WR}}$  and the internal energy of the shocked wind (bubble)  $E$ . A similar problem for the shell pushed by a pulsar wind has been solved earlier (Reynolds & Chevalier 1984). The difference is in the adiabatic index: here we have  $\gamma = 5/3$  instead of  $4/3$ . The equation of motion of the shell is then

$$M \frac{d^2 r}{dt^2} = \frac{2E}{r}, \quad (7)$$

while the energy equation is

$$\frac{dE}{dt} = L_{\text{WR}} - \frac{2E}{r} \frac{dr}{dt}. \quad (8)$$

The solution of these equations is the self-similar evolution of the CS shell radius

$$r = \left( \frac{2L_{\text{WR}}}{3M} \right)^{1/2} t^{3/2}. \quad (9)$$

To apply this solution to the phase III of the CS shell expansion, we identify the period  $t_{\text{II}} < t < t_{\text{III}}$  with the time taken by the CS shell to expand in the self-similar regime from the radius  $r_{\text{II}}$  at  $t = t_{\text{II}}$  to the final radius  $r_{\text{III}}$ .

For the parameters adopted in model B and the maximum mass-loss rate during stage I ( $\dot{M}_{\text{rsg}} \approx 0.01 M_{\odot} \text{ yr}^{-1}$ ), the phases I, II, and III end at  $t_{\text{I}} = 260 \text{ yr}$ ,  $t_{\text{II}} = 480 \text{ yr}$ , and  $t_{\text{III}} \approx 830 \text{ yr}$  respectively. The CS shell velocity at the moment  $t_{\text{III}}$  is  $v_{\text{III}} = 55 \text{ km s}^{-1}$ . The existence of the acceleration phase  $t_{\text{II}} < t < t_{\text{III}}$  provides in this case a natural mechanism for the fragmentation of the CS shell by the growth of the Rayleigh-Taylor instability (Garcia-Segura et al. 1996). The minimum mass-loss rate at stage I, determined from the requirement that stage II should end just prior to the SN explosion, is  $\dot{M}_{\text{rsg}} \approx 0.002 M_{\odot} \text{ yr}^{-1}$ . In this case  $t_{\text{I}} = 1400 \text{ yr}$ ,  $t_{\text{II}} = 2000 \text{ yr}$ , and the shell velocity is  $33 \text{ km s}^{-1}$ .

We thus conclude that a major mass-loss episode with the rate  $(2 - 10) \times 10^{-3} M_{\odot} \text{ yr}^{-1}$  took place 1000–2000 yr before the SN explosion. The WR wind accelerated this shell up to velocity of 30–50  $\text{km s}^{-1}$ .

## 5.2. Density of the CS Shell

The minimum density in the CS shell predicted by our models is  $n \geq 2 \times 10^7 \text{ cm}^{-3}$  (§ 4.3). This value should reflect the pressure and thermal balance at the latest phase of the

interaction of the WR wind with the CS shell. The dynamical pressure created by the WR wind is

$$p_{WR} \approx \frac{\dot{M}_{WR} v_{WR}}{4\pi R^2}. \quad (10)$$

For the parameters adopted above ( $\dot{M}_{WR} = 10^{-5} M_{\odot} \text{ yr}^{-1}$ ,  $v_{WR} = 1000 \text{ km s}^{-1}$ ,  $R = 6.5 \times 10^{16} \text{ cm}$ ) this expression leads to  $p_{WR} \approx 10^{-6} \text{ dyn cm}^{-2}$ . Because  $p_{WR}$  is actually determined by the pressure at the WR wind termination shock, the pressure could be a factor  $\sim 30$  higher than this estimate if the wind bubble is contained within the shell. However, if the bubble can break out of the shell because of instabilities, the pressure is reduced. We regard this pressure estimate as a lower limit. To derive the density from pressure equilibrium one needs to know the temperature of the compressed CS gas. First, we check that the CS shell was mostly neutral.

The ionizing radiation of the presupernova forms a low density HII zone. The density of the HII zone in pressure equilibrium is  $n_2 = p_{WR}/kT_2 \approx 7 \times 10^5 \text{ cm}^{-3}$  assuming  $T_2 = 10^4 \text{ K}$ . The column density of the HII zone is

$$N_2 = \frac{L_{UV}}{4\pi R^2 \alpha n_2 \text{Ry}}, \quad (11)$$

where  $L_{UV}$  is the luminosity of the ionizing radiation,  $\alpha$  is the hydrogen recombination coefficient, and Ry is the hydrogen ionization potential. The luminosity of the progenitor, assuming a helium core of a  $15 M_{\odot}$  star, is  $L = 2 \times 10^{38} \text{ erg s}^{-1}$  (Meynet et al. 1994). Adopting  $L_{UV} = 0.5L \approx 1 \times 10^{38} \text{ erg s}^{-1}$ ,  $T_2 = 10^4 \text{ K}$ ,  $\alpha = 2 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ , and  $R = 6.5 \times 10^{16} \text{ cm}$ , we obtain  $N_2 \approx 6 \times 10^{20} \text{ cm}^{-2}$ . This is substantially lower than the hydrogen column density of the CS shell,  $\sim 6 \times 10^{22} \text{ cm}^{-2}$  for a CS shell with a mass of  $2.7 M_{\odot}$ . This estimate implies that the presupernova radiation ionizes only a small fraction of the CS shell and the bulk of the CS shell is neutral and can be referred to as a photodissociation region (Tielens & Hollenbach 1985).

The cool neutral CS shell with a column density of  $N_H \approx 6 \times 10^{22} \text{ cm}^{-2}$  is characterized by a dust extinction  $A_V \sim 10$ , assuming interstellar dust properties (Spitzer 1978). In a photodissociation zone with dust extinction  $A_V \geq 4$  the gas temperature follows the dust temperature owing to the gas heating by the dust IR radiation (Tielens & Hollenbach 1985). With the emission efficiency of the dust at the maximum of the blackbody infrared emission  $Q_e = a/\lambda \approx 3.4aT_d$  (here  $a$  is the grain radius), the temperature of the dust grains should be  $T_d \approx (L/55\pi R^2 a \sigma)^{1/5}$ . With  $L = 2 \times 10^{38} \text{ erg s}^{-1}$ ,  $R = 6.5 \times 10^{16} \text{ cm}$  and  $a = 10^{-6} \text{ cm}$ , we obtain  $T_d \approx 300 \text{ K}$ . Gas with this temperature in equilibrium with the pressure  $p_{WR}$  has a density  $n \sim 2 \times 10^7 \text{ cm}^{-3}$ . This is consistent with the lower limit for the density of CS shell clouds. The suggested scenario of the CS shell formation thus seems realistic.



## 6. DISCUSSION AND CONCLUSIONS

Our goal was to propose a model for the strong late time X-ray, radio, and  $H\alpha$  emission from the Type Ib/c supernova SN 2001em. We developed a picture in which the SN ejecta of a normal SN Ib/c collide with a dense massive CS shell ( $M_{\text{cs}} \sim 3 M_{\odot}$ ) at a radius of  $\sim 0.7 \times 10^{17}$  cm. We found that two scenarios are viable: model A in which the dense CS shell not is yet overtaken by the time of X-ray observation (937 d) and model B with the CS shell overtaken prior to the X-ray observation. The mass loss episode that led to the formation of the CS shell was characterized by a high mass loss rate  $(2 - 10) \times 10^{-3} M_{\odot} \text{ yr}^{-1}$  at a stage 1000–2000 yr prior to the SN outburst. This material was then swept up by the fast WR wind from the presupernova progenitor. Rayleigh-Taylor instabilities likely led to the fragmentation of the CS shell which is manifested in the low X-ray and radio absorption despite the high column density of the shell.

The mechanism for the rapid loss of the  $3 M_{\odot}$  hydrogen envelope is not clear, although it is probably related to mechanisms for producing SN Ib/c presupernovae in a close binary scenario. The bulk of SN Ib/c presupernovae are thought to originate by the stripping of the hydrogen envelope at a late stage of binary star evolution as a result of mass transfer to a companion and/or the loss of the common envelope (van den Heuvel 1983; Ensman & Woosley 1988; Podsiadlowski, Joss, & Hsu 1992; Wellstein & Langer 1999). In the case of SN 2001em, we believe that common envelope evolution is the most likely mechanism of the formation of the massive CS shell. The 1000 – 2000 yr delay between a strong mass loss episode and the supernova explosion indicates that the former might happen at the stage of carbon burning in the core of a star with an initial mass in the range  $14 - 17 M_{\odot}$  (Hirshi, Meynet, & Maeder 2004). We suggest that the remains of the hydrogen envelope ( $\sim 3 M_{\odot}$ ) were lost during the carbon burning phase due to the formation of a common envelope in a binary system.

The relative fraction of SNe Ib/c passing through the common envelope phase is uncertain and lies between 10% (Podsiadlowski, Joss, & Hsu 1992) and nearly 100% (Tutukov & Yungelson 2002). The massive star acquires a red supergiant structure at the He burning stage. Therefore, most SN Ib/c presupernovae pass through the common envelope stage long before ( $\sim 10^6$  yr) the supernova explodes in the rarefied CS environment formed by the WR wind. Only a small fraction of SN Ib/c presupernovae lose their H envelope at the C burning stage. It was argued that this fraction is possibly about  $\sim 10^{-2}$  (Chugai 1997). We thus expect that roughly 0.001 – 0.01 of all SNe Ib/c possess close ( $R \lesssim 10^{17}$  cm) massive CS shells and display CS interaction by strong radio, optical and X-ray emission at an age of 1 – 10 yr. Upper limits on late radio emission from SNe Ib/c (Soderberg, Nakar, & Kulkarni 2005) seem to be consistent with the estimated fraction of these events.

The occurrence of the supernova close to the time that the H envelope was lost may have relevance to some Type IIn supernovae with strong circumstellar interaction. (Fransson et al. 2002) found that the ejecta in SN 1995N inside the reverse shock wave were heavy element rich, implying that this Type IIn supernova had lost essentially all the hydrogen envelope in a dense wind at the time of the supernova. It is unlikely, however, that the rate of all the Type IIn supernovae can be explained entirely by the common envelope events at the carbon burning phase (Chugai 1997).

In addition to radio detection, an efficient way to find SNe Ib/c with close CS shells could be the detection of late time  $H\alpha$  emission with a luminosity of  $\sim 10^{39} - 10^{40}$  erg s $^{-1}$  at an age of 1–10 yr, as has occurred for some Type IIn supernovae. Another interesting way to detect the presence of the massive close CS shell around SN Ib/c is related to the possibility that the shell is dusty. If the radius of the CS shell exceeds the dust evaporation radius  $\sim (1 - 3) \times 10^{17}$  cm, the observations of the infrared echo in the *KLM* bands may reveal the presence of a CS shell soon after the SN Ib/c explosion, similar to infrared dust echos observed from SN 1979C and SN 1980K (Bode & Evans 1980; Dwek 1983). These observations will also serve to distinguish late circumstellar interaction from misaligned gamma ray burst events, which must be present in the population of SNe Ib/c at some level.

We are grateful to Dave Pooley for kindly sending us the observed X-ray fluxes of SN 2001em. This research was supported in part by Chandra grant TM4-5003X and NSF grant AST-0307366.

## REFERENCES

- Bietenholz, M. F., & Bartel, N. 2005, *ApJ*, 625, L99
- Blondin, J. M. 2001, in *Young Supernova Remnants*, ed. S. S. Holt & U. Hwang (Melville, NY: AIP), 59
- Bode, M. F., & Evans, A. 1980, *MNRAS*, 193, 21P
- Chevalier, R. A. 1982, *ApJ*, 259, 302
- Chevalier, R. A. 1998, *ApJ*, 499, 810
- Chevalier, R. A., & Fransson, C. 1994, *ApJ*, 420, 268
- Chevalier, R. A., & Dwarkadas, V. V. 1995, *ApJ*, 452, L45
- Chevalier, R. A., & Liang, E. P. 1989, *ApJ*, 344, 332
- Chugai, N. N. 1992, *SvA*, 36, 63
- Chugai, N. N. 1997, *ARep*, 41, 672
- Chugai, N. N., Chevalier, R. A., & Lundqvist, P. 2004, *MNRAS*, 355, 627
- Collin-Souffrin, S., & Dumont, A. M. 1989, *A&A*, 213, 29
- Cox, A. N. 2000, *Allen’s Astrophysical Quantities* (New York: Springer)
- Dwarkadas, V. V. 2005, *ApJ*, 630, 892
- Dwek, E. 1983, *ApJ*, 274, 175
- Ensman, L. M., & Woosley, S. E. 1988, *ApJ*, 333, 754
- Filippenko, A. V. 1997, *ARA&A*, 35, 309
- Filippenko, A. V., & Chornok, R. 2001, *IAU Circ.* 7737
- Fransson, C., et al. 2002, *ApJ*, 572, 350
- Garcia-Segura, G., Langer, N., & Mac Low, M.-M. 1996, *A&A*, 316, 133
- Gieseler, U. D. J., Jones, T. W., & Kang, H. 2000, *A&A*, 364, 911
- Granot, J., & Ramirez-Ruiz, E. 2004, *ApJ*, 609, L9

- Heger, A., Jeannin, L., Langer, N., & Baraffe, I. 1997, *A&A*, 327, 224
- Hirshi, R., Meynet, G., & Maeder, A. 2004, *A&A*, 649, 2004
- Itoh, N., Sakamoto, T., Kasano, S., Nozawa, S., & Kohyama, Y. 2000, *ApJS*, 128, 125
- Kahn F. D. 1983, in *IAU Symp. 103, Planetary nebulae*, ed. D. R. Flower (Dordrecht: Reidel), 305
- Klein, R. I., McKee, C. F., & Colella, P. 1994, *ApJ*, 420, 213
- Kozma, C., & Fransson, C. 1992, *ApJ*, 390, 602
- Manchester, R. N., Gaensler, B. M., Wheaton, V. C., Staveley-Smith, L., Tzioumis, A. K., Bizunok, N. S., Kesteven, M. J., & Reynolds, J. E. 2002, *PASA*, 19, 207
- Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, *A&AS*, 103, 97
- Paczyński, B. 2001, *Acta Astron.*, 51, 1
- Papenkova, M., & Li, W. D. 2001, *IAU Circ.* 7722
- Paragi, Z., Garrett, M. A., Paczyński, B., Kouveliotou, C., Szomoru, A., Reynolds, C., Parsley, S. M., & Ghosh, T. 2005, in *Stellar End Products*, preprint (astro-ph/0505468)
- Podsiadlowski, P., Joss, P. C., & Hsu, J. J. L. 1992, *ApJ*, 391, 246
- Pooley, D., & Lewin, W. H. G. 2004, *IAU Circ.* 8323
- Reynolds, S. P., & Chevalier, R. A. 1984, *ApJ*, 278, 630
- Schlegel, D., Finkbeiner, D. & Davis, M. 1998, *ApJ*, 500, 525
- Soderberg, A. M., Gal-Yam, A., & Kulkarni, S. R. 2004, *GRB Circular Network*, 2586
- Soderberg, A. M., Nakar, E., & Kulkarni, S. R. 2005, *ApJ*, submitted (astro-ph/0507147)
- Spitzer, L., Jr. 1978, *Physical processes in the interstellar medium* (New York: Wiley & Sons)
- Stockdale, C. J., Van Dyk, S. D., Sramek, R. A., Weiler, K. W., Panagia, N., Rupen, M. P., & Paczyński, B. 2004, *IAU Circ.* 8282
- Stockdale, C. J., et al. 2005, *IAU Circ.* 8472
- Sutherland, R. S., & Dopita, M.A. 1993, *ApJS*, 88, 253

- Tielens, A. G. G. M., & Hollenbach, D. 1985, *ApJ*, 291, 722
- Tutukov, A. V., & Yungelson, L. R. 2002, *ARep.*, 46, 738
- Utrobin, V. P. 1994, *A&A*, 281, L89
- van den Heuvel, E. P. J. 1983 in *Accretion-driven stellar X-ray sources*, ed. W. H. G. Lewin & E. P. J. van den Heuvel (Cambridge: CUP), 303
- Verner, D. A., Yakovlev, D. G., Band, I. M., & Trzhaskovskaya, M. B. 1993, *At. Data Nucl. Data Tables*, 55, 233
- Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salvati, M. 1986, *ApJ*, 301, 790
- Wellstein S., & Langer N. 1999, *A&A*, 350, 148
- Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. 1994, *ApJ*, 429, 300
- Zel’dovich, Ya. & Raizer, Yu.A. 1967, *Physics of shock waves and high temperature hydrodynamic phenomena* (New York: Academic)

Table 1: Model parameters

Parameter	Units	A	B
$R_1$	$10^{16}$ cm	6.3	5.3
$R_2$	$10^{16}$ cm	7	5.9
$w_2$	$10^{17}$ g cm $^{-1}$	7	6
$M_{\text{cs}}$	$M_{\odot}$	3.1	2.3

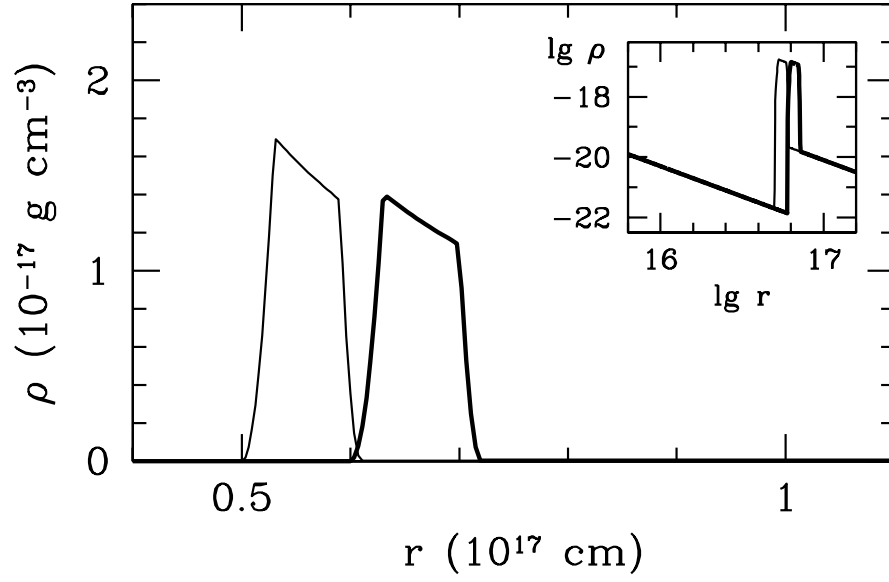


Fig. 1.— The circumstellar density distribution for model A (*thick line*) and model B (*thin line*) (see Table 1). Inset: the same distributions in logarithmic coordinates.

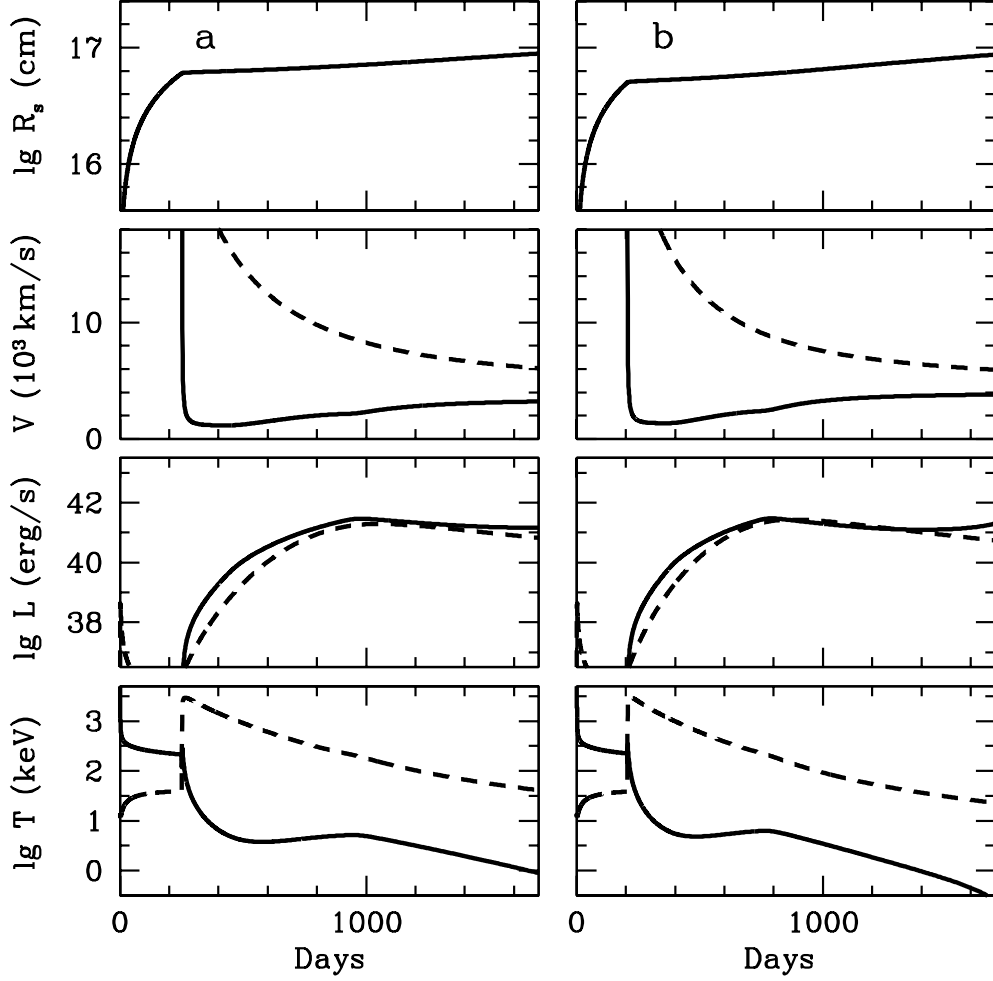


Fig. 2.— Evolution of the circumstellar interaction of SN 2001em: model A on the left (a) and model B on the right (b). The plot shows from top to bottom the radius of the thin shell, the expansion velocity of the thin shell (*solid*) and the SN ejecta velocity at the reverse shock (*dashed*), the unabsorbed X-ray luminosity of the forward shock (*solid*) and reverse shock (*dashed*), and the temperature of the shocked CS gas (*solid*) and shocked SN gas (*dashed*).



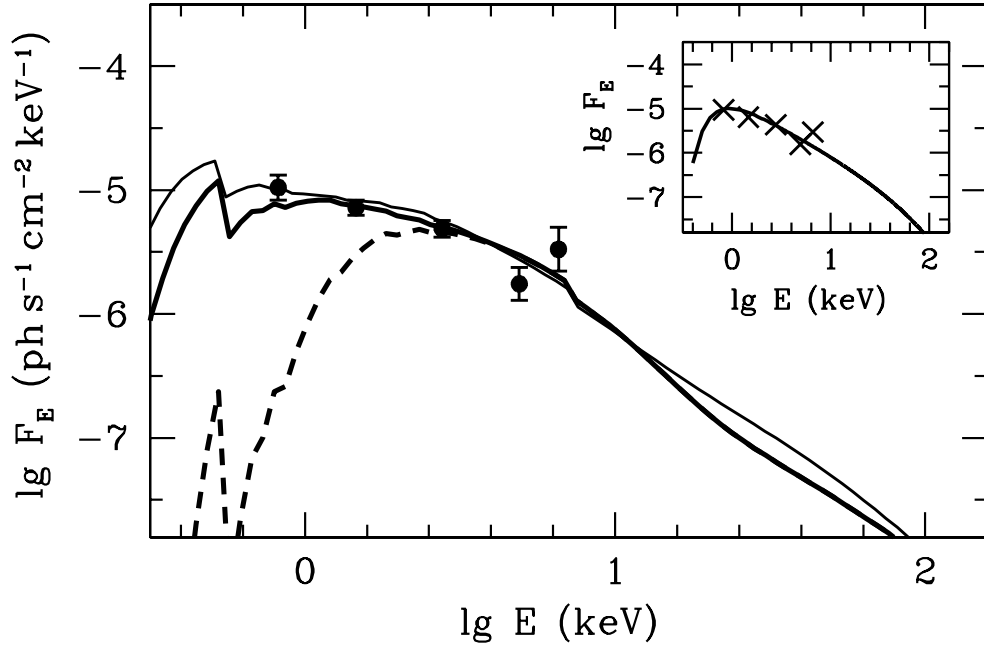


Fig. 3.— The photon spectrum of escaping X-ray radiation on day 937. Both model A (*thick line*) with a clumpy CS shell and model B (*thin line*) show satisfactory agreement with the observed fluxes (Pooley & Lewin 2004). The models include the absorption by the clumpy cool H $\alpha$ -emitting gas in the forward shock. The fits are comparable to the fit of an isothermal hot gas ( $T = 80$  keV) model with an external cool absorber with  $N_{\text{H}} = 1.6 \times 10^{21} \text{ cm}^{-2}$  (see inset, Pooley & Lewin 2004). Model A with a smooth CS shell (*dashed line*) shows unacceptably strong absorption.

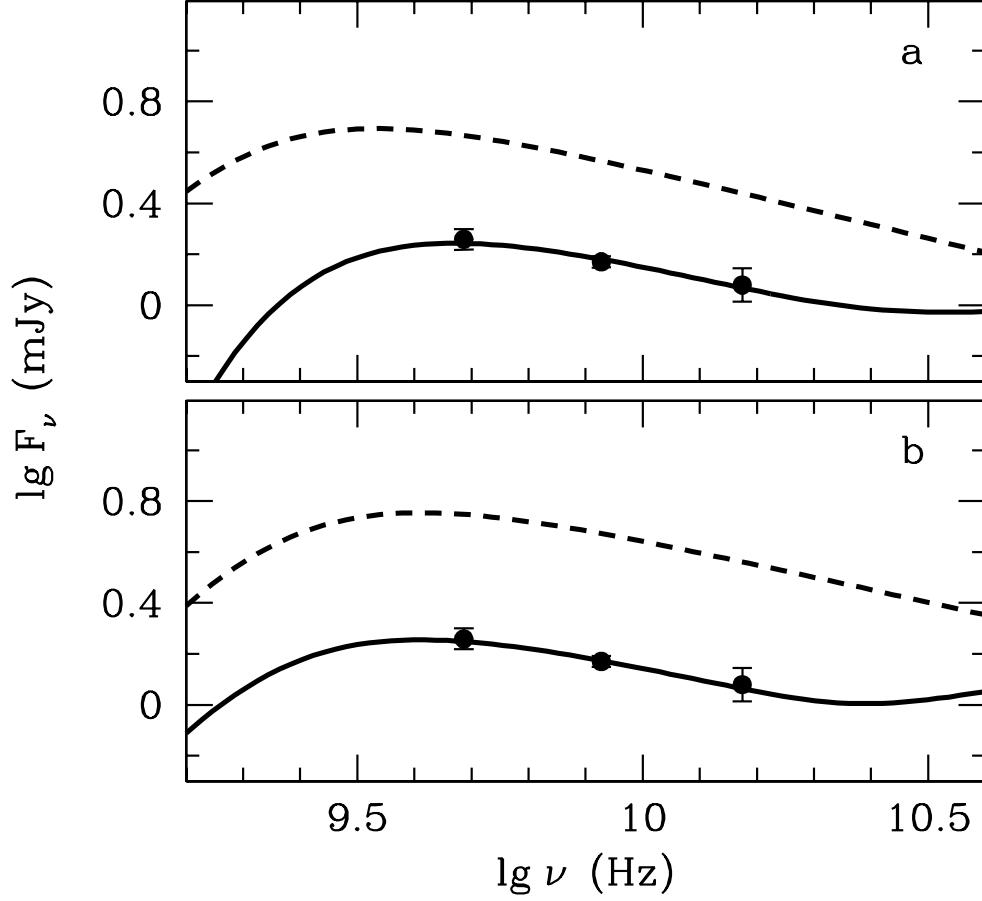


Fig. 4.— The model radio spectrum compared to the data of Stockdale et al. (2004) (*dots*). The *upper* panel shows the radio spectrum for model A without free-free absorption (*dashed line*) and with free-free absorption (*solid line*) produced by a clumpy CS shell and H $\alpha$ -emitting gas in the forward shock. The *lower* panel is the same as the upper panel but for model B and the free-free absorption produced only by H $\alpha$ -emitting gas in the forward shock.